(54) Title: PNEUMATIC HUMAN POWER AMPLIFIER MODULE

(57) Abstract

A pneumatic human power amplifier module is usable in conjunction with a wide variety of pneumatic actuators and lifting devices to provide a human power amplifier for lifting a load. The module includes an end–effector (222), an electronic controller (221), and a pneumatic circuit (220). The end–effector contains a human interface subsection (224) which is grasped by a human operator and a load interface subsection (225) which engages the load (219) to be lifted. A force sensor in the end–effector detects the force imposed by the operator on the end–effector and transmits a signal representing the magnitude of the force to the controller. The controller in turn sends a command to the pneumatic circuit, which controls the flow of air into the associated pneumatic actuator (211). The actuator drives the lifting device (217). The controller and the pneumatic circuit are arranged such that the lifting device and the operator share the burden of lifting the load, with the operator supplying a predetermined percentage of the total force required to lift the load regardless of the size of the load.

PNEUMATIC HUMAN POWER AMPLIFIER MODULE

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FIELD OF THE INVENTION

The present invention relates to material handling devices and, more specifically, to a material handling device that amplifies the force a human exerts when the human lifts or lowers an object in the vertical direction.

BACKGROUND OF THE INVENTION

Several types of material handing devices are known. One type of material handling device, known as a balancer, consists of a motorized take-up pulley, a rope which wraps around the pulley when the pulley turns, and an end-effector which is attached to the end of the rope. The end-effector has components that connect to the load being lifted. The rotation of the pulley winds or unwinds the rope and causes the end-effector to lift or lower the load. In this class of material handling system, an upward force in the rope exactly equal to the gravity force of the object being lifted is generated by an actuator; the rope tension is equal to the weight of the object. Therefore, the only force the operator must impose to maneuver the object

is the force necessary to overcome the object's

inertia. This force can be substantial if the mass of

the object is large. Therefore, the ability to

accelerate or decelerate a heavy object is limited by

5 the operator's strength.

There are two ways of creating a force in the rope

so that it is exactly equal to the object weight.

First, if the system is pneumatically powered, the air

pressure is adjusted so that the lift force equals the

10 weight of the load. Second, if the system is

electrically powered, the correct voltage or current

(depending on the control circuitry) is provided to an

amplifier to generate a lift force that equals the load

weight. These types of systems are not suited to

15 maneuvers in which objects of varied weights are

lifted. This is true because each object requires a

different bias force to cancel its weight force. This

annoying adjustment can be done either manually by the

operator or electronically by measuring the object

20 weight.

For example, the BA Series of balancers made by

Zimmerman International Corporation work based on the

above principle. The air pressure is set and

controlled by a valve to maintain a constant load

25 balance. The operator has to manually reach the

actuator and set the system to a particular pressure to

generate a constant tensile force on the rope.

The LIFTRONIC System machines made by Scaglia of

Italy also belong to the family of balancers, but they

30 are electrically powered. As soon as the system grips

-2-

the load, the LIFTRONIC machine creates an upward force

in the rope which is equal and opposite to the weight

of the object being held. These machines may be

considered superior to the Zimmerman BA Series

5   balancers because they have an electronic circuit that

balances the load during the initial few moments when

the load is grabbed by the system. As a result, the

operator does not have to reach the actuator on top and

adjust the initial force in the rope. In this system,

10   the load weight is measured first by a force sensor in

the system. While this measurement is being performed,

the operator should not touch the load, but instead

should allow the system to find the object's weight.

If the operator does touch the object, the force

15   reading will not be correct. The LIFTRONIC machine

then creates an upward force in the rope which is equal

and opposite to the weight of the object being held.

          Balancers of the kind described above do not give

the operator a sense of the force required to lift the

20   load. Also, only the weight of the object is canceled

by the rope's tension. Moreover, such balancers are

generally not versatile enough to be used in situations

in which load weights vary.

          Another class of machines is similar in

25   architecture to the machines described above, but the

operator uses an intermediary device such as a valve,

pushbutton, keyboard, switch, or teach pendent to

adjust the lifting and lowering speed of the object

being maneuvered. For example, the more the operator

30   opens the valve, the greater the speed generated to

lift the object. With an intermediary device, the operator is not in physical contact with the load being lifted, but is busy operating a valve or switch. The operator does not have any sense of how much he/she is
5   lifting because his hand is not in contact with the object. Although suitable for lifting objects of various weights, this type of system is not comfortable for the operator because the operator must focus on an intermediary device (i.e valve, pushbutton, keyboard,
10   or switch). Thus, the operator pays more attention to operating the intermediary device than to the speed of the object. This makes the lifting operation rather unnatural.

15   SUMMARY OF THE INVENTION

       All of the foregoing deficiencies are overcome in a human power amplifier according to this invention.

       The human power amplifier includes an end-effector to be held by a human operator; an actuator such as an
20   electric or air-powered or hydraulic motor; a computer or other type of controller for controlling the actuator; and a rope, cable, wire, bar or other force transmission member for transmitting a lifting force from the actuator to the end-effector. The end-
25   effector provides an interface between the human operator and an object which is to be lifted. A force transfer mechanism such as a pulley, drum or winch is used to apply the force generated by the actuator to the rope or other member which transmits the lifting
30   force to the end-effector. (Note that the word

-4-

"lifting" herein refers to both lifting and lowering
motions.)

The end-effector includes a human interface
subsystem and a load interface subsystem. The load
5   interface subsystem in configured so as to grip or
otherwise attach to the load and may include, for
example, a suction cup, a magnet, or a mechanical
member shaped to conform to a surface of the load. The
human interface subsystem includes a force sensor which
10   is mounted so as to measure the vertical force imposed
on the end-effector by the human operator. A wide
variety of force sensors may be used, including strain
gauges, load cells, and piezoelectric devices. The
vertical force on the end-effector may also be detected
15   by measuring the displacement of a resilient element
such as a spring.

A signal representing the vertical force imposed
on the end-effector by the human operator, as measured
by the force sensor, is transmitted to the controller
20   which is associated with the actuator. The controller
causes the actuator to lift the end-effector
appropriately so always only a pre-programmed small
proportion of the load force is lifted by the human
operator, with the remaining force being provided by
25   the actuator. Therefore, the actuator adds effort to
the lifting task only in response to the operator's
hand force. With this load sharing concept the
operator has the sense that he or she is lifting the
load, but with far less force than would ordinarily be
30   required. The force applied by the actuator takes into

-5-

account both the gravitational and inertial forces that
are necessary to move the load. Since the force
applied by the actuator is automatically determined by
the force applied to the end-effector by the operator,

5   there is no need to set or adjust the human power
amplifier for loads having different weights.

There is no switch, valve, keyboard, teach
pendent, or pushbutton in the human power amplifier to
control the lifting speed of the load. Rather, the

10   contact force between the human hand and the end-
effector is used to control the lifting speed of the
load. The human hand force is measured, and these
measurements are used by the controller to calculate
the required speed of the force transmission member so

15   as to create sufficient mechanical strength to assist
the operator in the lifting task. In this way, the
device follows the human arm motions in a "natural"
way. When the human uses this device to manipulate a
load, a well-defined small portion of the total force

20   (gravity plus acceleration) is lifted by the human.
This force gives the operator a sense of how much
weight he/she is lifting. Conversely, when the
operator does not apply any vertical force (upward or
downward) to the end-effector, the actuator does not

25   move the force transmission member at all, and the load
remains motionless.

In one embodiment, the actuator comprises an
electric motor with a transmission and the force
transmission member comprises a rope from which the

30   end-effector is suspended. A single end-effector can

be used, with the operator gripping the end-effector

with one hand, or a pair of end-effectors connected to

the actuator, preferably by means of a pulley

arrangement, can be used, with the operator gripping

5   one of the end-effectors in each hand.

Another group of embodiments comprise a pneumatic

human power amplifier module which can be used in

conjunction with a variety of pneumatic material

handling devices, typically including a pneumatic

10   actuator and a lifting device. The pneumatic human

power amplifier module is highly versatile and in

effect converts a conventional pneumatic material

handling device into a human power amplifier.

The pneumatic human power amplifier module

15   includes an end-effector, an electronic controller, and

a pneumatic circuit including a proportional servovalve

and optionally a directional servovalve, . The end-

effector is connected to the pneumatic material

handling device, and provides an interface between the

20   device and a human operator.

A signal representing the vertical force imposed

on the end-effector by the human operator is measured

by a force sensor within the end-effector and is

transmitted to the electronic controller. The

25   controller in turn sends a command to the pneumatic

circuit, thereby operating the proportional servovalve

and causing the pneumatic actuator to move the material

handling device appropriately so the human operator

lifts a pre-programmed (typically smaller) portion of

30   the load force. The actuator lifts the remaining

-7-

(typically larger) portion of the load force. The
measured force of the human against the end-effector is
used by the controller to calculate the correct speed
of the actuator. The actuator in turn creates

5   sufficient mechanical force in the material handling
device to assist the operator in the lifting task.

In one group of embodiments the pneumatic circuit
also includes a directional servovalve associated with
a pair of UP and DOWN switches which allow the

10   proportional servovalve to be bypassed in situations,
for example, when the operator is not attending the
end-effector or a component of the controller is
malfunctioning.

Thus a material handling device equipped with a

15   pneumatic human power amplifier module of this
invention amplifies the force that the human exerts
when the human uses the end-effector to lift or lower
an object: that is, the material handling device lifts
a pre-programmed larger percentage of the total force

20   of the load (i.e., gravity plus acceleration), while
the human lifts the remaining smaller percentage of the
total load force. The contact force between the human
and the end-effector is used to control the actuator
and consequently the motion of the during load

25   manipulation. This contact force is felt as a feedback
by the human operator, providing a sense of how much
weight he/she is lifting.

Existing manual material handling devices have
pneumatic actuators which usually power a single degree

30   of freedom. The system is arranged such that this

-8-

degree of freedom contributes primarily to lifting and
lowering the load.

Using the power amplifier module there is no need
to set or adjust the actuator for loads of different
5   weights, because the force applied by the actuator to
the load is determined automatically by the electronic
controller, based on the force applied by the operator
to the end-effector and on the dynamic behavior of the
manual material handling device.

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BRIEF DESCRIPTION OF THE DRAWING
Fig. 1 illustrates an embodiment of the human
power amplifier which includes a single end-effector.
Fig. 2 illustrates an embodiment of the human
15   power amplifier which includes a pair of end-effectors.
Fig. 3 illustrates a detailed view of a first
embodiment of an end-effector.
Fig. 4 illustrates a modified version of the end-
effector shown in Fig. 3 including support plates for
20   connecting the end-effector to a brace for the
operator's hand and/or arm.
Fig. 5 illustrates an embodiment of a brace.
Fig. 6 illustrates a cross-sectional view of an
embodiment of an end-effector, showing in particular
25   the structure of the force sensor.
Fig. 7 illustrates a human power amplifier system
with a pair of end-effectors which is designed to lift
a human (e.g., a patient from a wheelchair).
Fig. 8 illustrates a cross-sectional view of an
30   embodiment of an end-effector which includes a

-9-

displacement detector for measuring the force imposed
on the end-effector by an operator.

Fig. 9 illustrates a cross-sectional view of an
alternative embodiment of an end-effector which
5   includes a displacement detector for measuring the
force imposed on the end-effector by an operator.

Fig. 10 illustrates a schematic diagram of the
manner in which the operator and load forces interact
with the elements of the human power amplifier to
10   provide a movement to a load.

Fig. 11 is a perspective view of a pneumatic human
power amplifier module according to this invention
arranged so as to control a ceiling-hung pneumatic
material handling device containing a single-acting
15   translational actuator.

Fig. 11A is a cutaway side view of the single-
acting transational pneumatic actuator shown in Fig.
11, showing the internal pulley ,ball-nut, ball-screw
and piston.

20   Fig. 12 is a perspective view of the pneumatic
human power amplifier module arranged so as to control
a ceiling-hung pneumatic material handling device
containing a different form of single-acting
translational actuator.

25   Fig. 13 is a perspective view of the pneumatic
human power amplifier module arranged so as to control
a pedestal-mounted multi-degree-of-freedom pneumatic
material handling manipulator containing a single-
acting translational actuator.

Fig. 14 is a perspective view of the pneumatic
human power amplifier module arranged so as to control
a ceiling-hung multi-degree-of-freedom pneumatic
material handling manipulator containing a single-
5   acting translational actuator.

Fig. 15 is a schematic diagram showing a pneumatic
circuit without manual override

Fig. 16 is a schematic diagram showing a pneumatic
circuit with manual override

10   Fig. 17 is a perspective view of an embodiment of
an end-effector

Fig. 18 is a cross-sectional partially broken-away
view of the end-effector showing a displacement
detector for measuring the force imposed on the end-
15   effector by an operator.

Fig. 19 is a schematic diagram illustrating the
manner in which the operator, actuator and load forces
interact with the elements of the pneumatic human power
amplifier module

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DETAILED DESCRIPTION OF THE INVENTION

Fig. 1 illustrates a first embodiment of the
invention, showing a human power amplifier 10. At the
top of the device, a take-up pulley 11, driven by an
25   actuator 12, is attached directly to a ceiling, wall,
or overhead crane (not shown). Encircling pulley 11 is
a rope 13. Rope 13 is capable of lifting or lowering a
heavy load when the pulley 11 turns. Attached to rope
13 is an end-effector 14, which includes a human
30   interface subsystem 15 (including a handle 16) and a

-11-

load interface subsystem 17, which in this embodiment

includes a suction cup 18. Also shown is an air hose

19 for supplying suction cup 18 with low-pressure air.

Actuator 12 is driven by an electronic controller 20,

5   which receives signals from end-effector 14 over a

signal cable 21.

In one embodiment actuator 12 is an electric motor

with a transmission, but alternatively it can be an

electrically-powered motor without a transmission, an

10   air powered rotary actuator with or without

transmission, an air-powered linear actuator with a

mechanical transmission to convert the linear motion to

rotary motion, a hydraulic rotary actuator, or a

hydraulic linear actuator with a mechanical

15   transmission to convert the linear motion to rotary

motion. As used herein, transmissions are mechanical

devices such as gears, pulleys and ropes which increase

or decrease the tensile force in the rope. Pulley 11

can be replaced by a drum or a winch or any mechanism

20   that is able to convert the motion provided by actuator

12 to a vertical motion which lifts and lowers rope 13.

Although in this embodiment actuator 12 directly powers

the take-up pulley 11, one can mount actuator 12 at

another location and transfer power to take-up pulley

25   11 via another transmission system such as an assembly

of chains and spockets. Controller 20 can be an analog

circuit, a digital circuit, or a computer with input

output capability.

Human interface subsystem 15 is designed to be

30   gripped by a human hand and measures the *human force*,

-12-

i.e., the force applied by the human operator against
human interface subsystem 15. Load interface subsystem
17 is designed to interface with the load contains
various holding devices. The *load force* is defined as
5   the force imposed by the load on load interface
subsystem 17. The design of the load interface
subsystem depends on the geometry of the object being
lifted and other factors related to the lifting
operation. In addition to the suction cup 18 shown in
10 Fig. 1, hooks and grippers are examples of other means
that connect to load interface subsystems. For lifting
heavy objects, the load interface subsystem may contain
several suction cups.

The human interface subsystem 15 of end-effector
15 14 contains a sensor (described below) which measures
the magnitude of the vertical force exerted by the
human operator. If the operator's hand pushes upward
on the handle 16, the take-up pulley 11 moves the end-
effector 14 upward. If the operator's hand pushes
20 downward on the handle 16, the take-up pulley moves the
end-effector 14 downward. The measurements of the
forces from the operator's hand are transmitted to the
controller 20 over signal cable 21. Using these
measurements, the controller 20 calculates the amount
25 of pulley rotation necessary to either raise or lower
the rope 13 the correct distance to create enough
mechanical strength to assist the operator in the
lifting task as required. Controller 20 then commands
actuator 12 to cause pulley 11 to rotate. All of this
30 happens so quickly that the operator's lifting efforts

-13-

and the device's lifting efforts are for all purposes

synchronized perfectly. The operator's physical

movements are thus translated into a physical assist

from the machine, and the machine's strength is

5   directly and simultaneously controlled by the human

operator. In summary, the load moves vertically

because of the vertical movements of both the operator

and the pulley.

In this mode of operation, for more stability, one

10   might use an end-effector with two handles. In this

case, only one handle needs to be instrumented. For

lifting heavy objects, one can use two human power

amplifiers similar to the human power amplifier 10

shown in Fig. 1, one for the left and one for the right

15   hand.

A second embodiment of the invention is shown in

Fig. 2. In this embodiment, the operator must use both

his/her hands to lift the object. In this embodiment,

the operator can orient the object being lifted without

20   introducing any other motion to the object.

In the human power amplifier 20 shown in Fig. 2,

hanging from pulley 11 is a rope 22. This rope is

connected to the horizontal midpoint of a bar 23.

Hanging from each end of bar 23 is a single pulley: a

25   left pulley 27L at one end and a right pulley 27R at

the other end. Pulleys 27L and 27R are not motorized,

but are free to rotate in response to forces on the

single continuous rope 29 that runs over pulleys 27L

and 27R. Because pulleys 27L and 27R can rotate

30   freely, rope 29 moves freely whenever a force is

-14-

applied at either end of rope 29; if the end beneath
pulley 27L is pulled downward, the end beneath pulley
27R moves upward, and vice versa. End-effectors 24L
and 24R, connected to the ends of rope 29, are similar
5   to end-effector 14 shown in Fig. 1, except that suction
cup 18 has been omitted and angle pieces 28L and 28R
are suited to lifting a box 30.

End-effectors 24L and 24R include human interface
subsystems 25L and 25R, respectively. The magnitudes
10   of the vertical forces from the operator's hand
movements are measured by sensors (described below)
within human interface subsystems 25L and 25R and
transmit signals to controller 20 over signal cables
21L and 21R. The sensors within end-effectors 24L and
15   24R electronically detect the vertical forces from the
operator's hands, such as an upward movement of the
hands to lift box 30. If both of the operator's hands
push upward on the handles, the pulley 11 moves the
load-supporting system upward. If both of the
20   operator's hands push downward on the handles, the
take-up pulley moves the load-supporting system
downward. If the operator pushes upward on one end-
effector and downward on the other end-effector, the
net force measured by the force sensors is zero, so the
25   pulley 11 does not rotate, and thus the entire device
does not move. However the operator can now rotate the
object. In this embodiment, only one end-effector
(either left or right) can be instrumented. For a
given controller, the force amplification (described
30   below) when only one end-effector is instrumented, is

-15-

smaller than the force amplification when both end-
effectors are instrumented.

    Several embodiments of the end-effector will now
be described.

5   The first embodiment is shown in Fig. 3. End-
effector 40 is connected to a rope 41 and includes a
human interface subsystem 42 and a load interface
subsystem 43. Rope 41 could be, for example, either
rope 13 (Fig. 1) or rope 29 (Fig. 2)

10   A force sensor 44 is installed between a handle 45
and a bracket 46 to measure the human force in the
vertical direction on handle 45. Handle 45 is held by
the operator. If handle 45 is pushed up or down, force
sensor 44 measures the human force. Handle 45 is shown

15   as a cylinder in Fig. 3, but it can be of any shape
that is comfortable for the operator. For example, a
horizontally oriented circular bar (similar to a
steering wheel) can be connected to handle 45 at its
center to enable the operator to grasp handle 45 from

20   any direction.

    A bracket 46 is connected to the rope 41.
Although the right-hand side of bracket 46 can connect
to various load interface devices such as suction cups
or hooks, in the embodiment shown in Fig. 3 bracket 46

25   is welded to an angular bracket 47, which is used to
hold an edge or a corner of a box. This makes the end-
effector suitable for maneuvering in a system of the
kind shown in Fig. 2, wherein a pair of end-effectors
contact a load at two locations and are capable of

30   rotating the load about its own axis. Angular bracket

47 touches a plate 48 which is connected to handle 45,
but these two elements can freely slide vertically
relative to each other because they are not connected.
This free sliding motion between plate 48 and bracket

5   47 guarantees that the forces from the operator which
are in the vertical direction pass through force sensor
44 without any resistance, while the forces from the
operator which are not in the vertical direction are
transferred to bracket 47 through plate 48. If these

10 non-vertical forces were to pass through the force
sensor, they could either produce a false reading in
the sensor or damage the force sensor assembly.

In operation, the operator grips handle 45. If
the operator pushes downward on handle 45, force sensor

15 44 generates a positive signal proportional to the
downward force. If the operator pushes upward on
handle 45, force sensor 44 generates a negative signal
proportional to the human upward force.

A significant characteristic of end-effector 40 is

20 that force sensor 44 measures only the human force
imposed against the human interface subsystem 42, not
the load force (the force imposed on the load interface
subsystem by the load).

Fig. 4 shows a modified version of end-effector 40

25 with two support plates 49A and 49B that can connect to
a brace for the operator's hand and arm. This is
particularly useful when the human operator does not
grasp the handle with his or her fingers. Suppose, for
example, that handle 45 has a small radius and that the

30 distance between handle 45 and angular bracket 47 is so

-17-

small that the operator's fingers cannot wrap around

the handle 45. Adding plates 49A and 49B allows the

operator to exert force on handle 45 without holding it

with his or her fingers. Moreover, a brace 50, as

5   shown in Fig. 5, has been proven to create more

stability and comfort for some operators.

When the operator initiates an upward motion, the

human force which he or she exerts is recorded by the

force sensor. The signal then generated by the force

10   sensor is transmitted to the controller. The actuator

and the take-up pulley turn appropriately, causing an

upward motion of the rope and the end-effector

assembly. This lifts the load and the end-effector

together. Similarly, when the operator initiates a

15   downward motion, the actuator and the take-up pulley

turn appropriately, causing a downward motion of the

rope and the end-effector assembly.

Force sensor 44 can be selected from a variety of

force sensors that are available in the market,

20   including piezoelectric based force sensors,

metallic strain gage force sensors, semiconductor

strain gage force sensors, and force sensing resistors.

Regardless of the particular type of force sensor

chosen and its installation procedure, the design

25   should be such that the force sensor measures only the

human force against end-effector 40.

Fig. 6 shows a version of end-effector 40 which

measures the vertical human force via a different type

of force sensor installation. A force sensor 60, which

30   may be similar to force sensor 44, is installed between

-18-

a handle 61 and a bracket 62 and is connected to
controller 20 via signal cable 21. Force sensor 60 has
a threaded part 63 that screws into an inside bore
within handle 61, which is grasped by the human

5   operator. The other side of the force sensor 60 is
connected to bracket 62 via a cylinder 64. The outside
diameter of cylinder 64 is slightly smaller than the
inside diameter of handle 61. This clearance allows a
sliding motion between handle 61 and cylinder 64, which

10   guarantees that the forces from the operator which are
in the vertical direction pass through force sensor 60
without any resistance and that the forces from the
operator which are not in the vertical direction are
transferred to bracket 62 and not to force sensor 60.

15   If these non-vertical forces pass through force sensor
60, they may either introduce false readings in the
sensor or damage the force sensor assembly.

        Fig. 6 also shows support plates 65A and 65B which
can be connected to a brace for the operator's hand

20   and/or arm. Four retaining rings 66 fit into slots in
handle 61 to secure plates 65A and 65B and the brace to
handle 61. Bracket 62 bolts to various load interface
devices such as a hook or a suction cup (not shown).

        Fig. 7 show a modified version of the system shown

25   in Fig. 2, in which a pair of end-effectors 70L and 70R
are connected to C-shaped members 71L and 71R for
maneuvering patients from their wheelchairs to their
beds and vice versa. C-shaped members 71L and 71R,
which may be covered with a padded cushion, are to be

30   placed under the patient's armpits. C-shaped members

-19-

71L and 71R are connected to bracket 62 of the end-effector.

In a second group of embodiments, the force imposed by the operator against the end-effector is
5   measured by the displacement of the handle rather than a force sensor of the kind described above. The lower cost and ease of use of displacement measurement systems may make this type of end-effector more attractive in some situations.

10   A cross-sectional view of one embodiment of an end-effector of the second group is shown in Fig. 8. Similar to the end-effectors described above, end-effector 80 includes a human interface subsystem 81 and a load interface subsystem 82. Human interface
15   subsystem 81 includes a handle 83 which is grasped by the operator and thus measures the human force, not the load force. Load interface subsystem 82 includes a bracket 84 that bolts to a hook or a suction cup or any other type of device that can be used to hold an
20   object. An eyelet 84A is mounted in bracket 84 for connecting bracket 84 to a rope (not shown).

In end-effector 80 a ball-screw mechanism 85 translates the vertical displacement of handle 83 into a rotary displacement which is measured by an angle
25   measuring device 86. Handle 83 functions as the ball-nut portion of ball-screw mechanism 85. The screw 87 of ball-screw mechanism 85 is secured by the inner race of a bearing system 88. Bearing system 88, here a double row bearing, includes of any combination of
30   bearing(s) that allows rotation of screw 87 while

supporting vertical and horizontal forces. A pair of angular contact bearings could also be used. Because of the connection between screw 87 and the inner race of bearing system 88, the inner race and screw 87 turn

5   together. The outer race of the bearing system 88 is held in bracket 84 by a retaining ring 91 which is fixed to the bottom of bracket 84.

A shaft 89 extends from the lower end of screw 87 along the axis of handle 83. An upper coil spring 90

10 is positioned around screw 87 and between the upper end of handle 83 and retaining ring 91, and a lower coil spring 92 is positioned around shaft 89 between a stop 93 fixed to shaft 89 and a stop 94 formed in the interior of handle 83. Thus coil spring 90 urges

15 handle 83 downward, and coil spring 92 urges handle 83 upward, and together springs 90 and 92 allow handle 83 to move axially with respect to screw 87 and shaft 89. A stop 95 mounted at the lower end of shaft 89 provides a limit to the downward movement of handle 83.

20 Handle 83, which functions as the ball-nut of the ball-screw mechanism 85, is held by the operator. If handle 85 is moved up and down without any rotation, then screw 87 turns. The amount of rotation of screw 87 depends on the lead of screw 87. For example, if

25 the lead is 1/2", then for every 1/2" motion of handle 83, screw 87 turns one revolution.

Angle measuring device 86 connected to the top of bracket 84 measures the rotation of screw 87. Angle measuring device 86 can be an optical rotary encoder, a

30 magnetic rotary encoder, a rotary potentiometer, a RVDT

(Rotary Variable Differential Transformer), an analog resolver, a digital resolver, a capacitive rotation sensor or a Hall effect sensor. Angle measuring device 86 produces a signal proportional to the rotation of

5 screw 87. Springs 90 and 92 return handle 83 to an equilibrium position when handle 83 is not pushed. As shown in Fig. 8, the spring pushes the ball-nut upward so the bracket stops the ball-nut.

To maintain a tension in the rope, an upward

10 velocity is imposed on the rope when there is no load on the system (assuming that the end-effector itself is light). In this case, only one spring, a compression spring at the bottom of handle 83 or a tension spring at the top of handle 83, may be used to force handle 83

15 upward.

When using end-effector 80, the operator grasps handle 83. When the operator initiates an upward motion, handle 83 (the ball-nut) moves upward, causing screw 87 to turn (e.g., clockwise). This motion is

20 recorded by angle measuring device 86. The generated signal from angle measuring device 86 is then transmitted to controller 20 (Figs. 1 and 2). Actuator 12 turns pulley 11 appropriately, causing an upward motion of the rope and end-effector 80. This motion

25 lifts the load and the end-effector 80 together. Similarly, when the operator initiates a downward motion, actuator 12 and the pulley 11 turn appropriately in the opposite direction, causing a downward motion of the rope and end-effector 80.

-22-

Thus, in end-effector 80 the vertical displacement
of handle 83 relative to bracket 84 (which is
proportional to the human force) is measured, and the
measurement is fed to controller 20. Regardless of the
5 type of displacement sensor used in this device and its
installation procedure, this end-effector is designed
to measure only the human force in the vertical
direction. The end-effector does not measure the load
force. A safety switch 96 is installed to transfer the
10 actuator to another control mode (position control
mode) or to turn the system off when the operator
leaves the system.

Alternatively, ball-screw mechanism 85 in Fig. 8
can be replaced by a lead screw mechanism in which a
15 sliding movement between a nut portion and a screw
portion replaces the rolling motion of the balls.
Preferably, there should be little friction between the
nut portion and the screw portion, and the lead screw
mechanism should be back drivable.

20   In this group of embodiments a variety of
displacement sensors can be used to measure the spring
deflection. Fig. 9 shows an end-effector in which the
ball-screw mechanism is replaced with a ball spline
shaft mechanism. A handle 102, which is in the ball-
25 nut portion of the ball spline shaft mechanism, moves
freely along a spline shaft 100, with no rotation
relative to spline shaft 100. Balls 103 move in
grooves on spline shaft 100. Handle 102 is held by the
operator. A layer 104 of a foam like material can be

-23-

included in handle 102, so that the operator can grab
the handle more comfortably.

The right-hand side of bracket 101 is connected to
a rope via an eyelet 101A and has hole patterns that

5   allow for connection of a suction cup mechanism, a
hook, or any device to hold the object. An upper coil
spring 105 is positioned around spline shaft 100
between handle 102 and bracket 101 and urges handle 102
downward; similarly, a lower coil spring 106 is

10   positioned around spline shaft 100 between handle 102
and a stop 107 and urges handle 102 upward. A linear
motion detector 108 (e.g., a linear potentiometer or a
linear encoder) contains a probe 109 which contacts
bracket 101 so as to measure the motion of handle 102

15   relative to bracket 101. Linear motion detector 108
produces an electric signal on signal cable 19 which is
proportional to the linear displacement of handle 102
relative to bracket 101.

Linear motion detector 108 can be an optical

20   linear encoder, a magnetic linear encoder, a linear
potentiometer, a LVDT (linear variable differential
transformer), a capacitive displacement sensor, an eddy
current proximity sensor or a variable-inductance
proximity sensor. Fig. 9 shows a linear potentiometer

25   having its housing connected to handle 102 and its
probe 109 pushed against bracket 101. The motion of
probe 109 relative to the potentiometer housing creates
an electric signal proportional to the spring
deflection.

-24-

Alternatively, the ball spline shaft mechanism
shown in Fig. 9 can be replaced by a linear bushing
mechanism, wherein a bushing (slider) and a shaft slide
relative to one another with no balls. There should be
5   little friction between the bushing (slider) and the
shaft.

The sole purpose of the springs installed in the
end-effector is to bring the handle back to an
equilibrium position when no force is imposed on the
10   handle by the operator. Figs. 8 and 9 show the end-
effector using compression springs. One can use other
kinds of springs, such as cantilever beam springs,
tension springs or belleville springs in the end-
effector. Basically, any resilient element capable of
15   bringing the handle back to its equilibrium position
will be sufficient. The structural damping in the
springs or the friction in the moving elements of the
end-effectors (e.g. bearings) provide sufficient
damping in the system to provide stability.

20   Although not shown in the figures, one can install
one or several switches on the end-effectors described
herein to transfer the actuator to another control mode
(position control mode) or to turn the system off when
the operator leaves the system. A position controller
25   freezes the actuator and consequently the end-effector
at the position where it is when the operator leaves
the system.

As described above, the force or displacement
sensor in the end-effector delivers a signal to
30   controller 20 which is used to control actuator 12 and

-25-

to apply an appropriate torque to pulley 11. If e is

the input command to actuator 12 then, in the absence

of any other external torque on the actuator, the

linear velocity of the outermost point of the pulley or

5   the rope (v) can be represented by:

$$V = G \cdot e \qquad\qquad (1)$$

where G is the actuator transfer function.

10 In addition to the input command (e) from the

controller, the forces imposed on the end-effector also

affect the rope velocity. There are two forces imposed

on the end-effector which affect the rope velocity: a

force $(f_R + f_L)$ which is imposed by the operator's right

15 hand and left hand, and a force (p) which is imposed by

the load on the end-effectors (see Fig. 2). The input

command (e) and the forces on the end-effectors

contribute to the actuator speed such that:

20 $$v = G \cdot e + S(f_R + f_L + p) - V_{U/P} \qquad\qquad (2)$$

where S is the actuator sensitivity function which

relates the external forces to the rope velocity (v).

S is defined as the downward velocity of the rope (or

25 linear velocity of the outermost point on the pulley)

generated if one unit of impulse tensile force is

imposed on the rope. If a velocity controller is

designed for the actuator so that S is small, the

actuator has only a small response to the imposed

30 tensile force on the rope. A high-gain controller in

-26-

the closed-loop velocity system results in a small S
and consequently a small change in actuator velocity in
response to forces imposed on the rope. Also note that
a high ratio transmission system on the actuator

5   produces a small S for the system. Note that $(f_R + f_L +$
p) is the total tensile force in rope 13 assuming bar
23 has negligible mass in comparison with the other
forces. To develop tension in ropes 13, 22 and 29
(Figs. 1 and 2) at all times, an upward biased rope

10   velocity (V_{UP}) is introduced to the system.

A reasonable performance specification for the
actuator is the level of amplification of the human
force $(f_R + f_L)$ that is applied to the end-effector. If
the force amplification is large, a small force applied

15   by the operator results in a large force being applied
to the load via the rope. If the force amplification
is small, a small force applied by the operator results
in a small force being applied to the load via the
rope. Consequently, if the force amplification is

20   large, the operator "feels" only a small percentage of
the force required to lift the load. Importantly, the
operator still retains a sensation of the dynamic
characteristics of the free mass, yet the load
essentially "feels" lighter. With this heuristic idea

25   of system performance, the system performance can be
defined as a number that is referred to as the force
amplification factor. For example, when the force
amplification factor of the system is programmed to be
5, the force on the end-effector from the load is 5

30   times the force that the operator is applying to the

-27-

end-effector. The following explains how to guarantee
this for the amplifier. The human forces f_R and f_L are
measured and passed through controller 20, which
delivers a signal (e) to actuator 12. If the transfer
5   function of the controller is represented by K, then
the output of the controller, e, is equal to $K(f_R + f_L)$.

Substituting for e in equation (2) results in the
following equation for the rope velocity (v):

10
$$v = GK(f_R + f_L) + S(f_R + f_L + p) - V_{up}$$
(3)

Now suppose that the operator maneuvers two
different objects through similar trajectories. Since
the object weights are different from each other in
15   these two experiments, then the resulting force that
the operator experiences during each maneuver will be
different. Any change in the force from the load on
the end-effector due to variation of the object mass
(Δp) will result in a variation of the human force
20   according to the following equation if no change in
maneuvering speed is expected:

$$\left(\frac{GK}{S} + 1\right)(\Delta f_R + \Delta f_L) = -\Delta p$$
(4)

25   where Df_L and Df_R are the change in the human force on
the end-effector.

The term (GK/S +1) in equation (4) is the force
amplification factor. This term relates the change in
the load force (Δp) to the change in the human force

-28-

($\Delta f_R + \Delta f_L$). The larger K is chosen to be, the greater

the force amplification in the system. K must be

designed to yield an appropriate force amplification.

Fig. 10 shows diagrammatically how the human force and

5   load force are generated. As Fig. 10 indicates, K may

not be arbitrarily large. Rather, the choice of K must

guarantee the closed-loop stability of the system shown

in Fig. 10. The human force ($f_R + f_L$) is a function of

human arm impedance (H), whereas the load force (p) is

10   a function of load dynamics (E), i.e. the gravitational

and inertial forces generated by the load.

As described above, the device in Fig. 2 allows

the operator not only to lift, but also to rotate the

object. The torque required to rotate the object is

15   delivered entirely by the human without any assistance

from the device. Therefore, although the device shown

in Fig. 2 allows for small rotational maneuvers of the

object, highly accelerated rotations of the object are

not recommended. Similarly, lifting objects with an

20   uneven weight distribution requires torque which must

be supported by the human entirely and is not

recommended. In summary, the operator must make sure

that the weight of the object being lifted is in the

middle of the end-effectors. Moreover, if needed, the

25   objects must be rotated with very little acceleration.

It can easily be understood that under the above

assumption, the human forces on both end-effectors are

equal to each other: i.e. $f_R = f_L$ and equation (4)

reduces to

30

$$\left(\frac{2GK}{S} + 2\right)\Delta f_R = -\Delta p \qquad (5)$$

The above equation is also true for the left end-
effector.

5   As described above, in the operating with two end-
effectors one can install a force sensor on one of the
end-effectors only. If only the right end-effector has
a force sensor, then the analysis (similar to the
analysis above) reduces to:

10

$$\left(\frac{GK}{S} + 2\right)\Delta f_R = -\Delta p \qquad (6)$$

This indicates, for a given K, the force
amplification when only one end-effector is
15   instrumented is smaller than the force amplification
when both end-effectors are instrumented.

Note that if the system operates as shown in Fig.
1 (i.e. one end-effector only), then equation (4)
reduces to:

20

$$\left(\frac{GK}{S} + 1\right)\Delta f_R = -\Delta p \qquad (7)$$

Thus the end-effector electronically senses the
force from the human hand gripping the end-effector.
25   The measurement of the hand force is transmitted to the
device's controller. Using this measurement, the
controller calculates the amount of pulley rotation

-30-

necessary to either raise or lower the pulley rope the
correct distance to create enough mechanical strength
to assist the operator in the lifting task. In this
way, the end-effector follows the human arm motions in

5   a "natural" way. In other words the pulley, the rope,
and the end-effector mimic the lifting/lowering
movements of the human operator, and the human is able
to manipulate heavy objects more easily without the use
of any intermediary device.

10   The rope supports only a pre-programmed proportion
of the load forces (i.e., gravity plus inertial force
due to acceleration), not the entire load force; the
remaining force is supported by the operator. This
method of load sharing gives the operator a sense of

15   how much he/she is lifting. This is true because the
force the human is imposing on the end-effector is
exactly equal to a scaled-down value of the actual
force the load is imposing on the rope. The measured
signal from the end-effector, a signal representing the

20   human force, is used via a computer or electronic
circuitry to drive the actuator appropriately so that
only a pre-programmed small proportion of the load
force is lifted by the operator. Therefore the
actuator adds effort to the lifting task only in

25   response to the operator's hand force. For example, if
the human force is set to be 5% of the actual force
needed to lift the load, for every 50 lbs. of force
(gravity plus inertia force due to acceleration) the
pulley rope could supports 45 lbs. while the operator

30   feels and supports 5 lbs. The allocation of the load

forces between the pulley rope and the human is
programmable.

Another group of embodiments according to this
invention include a highly versatile pneumatic human
5   power amplifier module that can be used with a wide
variety of pneumatic material handling systems. The
pneumatic human power amplifier module in effect
converts a conventional pneumatic material handling
system into a human power amplifier system. Four
10   illustrative arrangements are shown in Figs 11-14. In
each of these embodiments the pneumatic human amplifier
module generally includes an end-effector, an
electronic controller and a pneumatic circuit
comprising a proportional servovalve and an optional
15   directional servovalve.

In existing manual material handling devices, a
simple pneumatic circuit with two manual valves
(usually thumb-operated), one for upward motion and one
for downward motion, lets air into and out of the
20   actuator for lifting and lowering the load. Such
manual operation with up/down valves is not natural for
the operator, because the operator is busy operating a
valve or a switch and is not in physical contact with
the load being lifted. Thus the operator does not have
25   any sense of how much he/she is lifting. With existing
manual material handling devices, the operator must
concentrate on operating the valves to achieve a
desired lifting speed for the load. But, when the
human amplifier module described here is part of the

-32-

device, the operator no longer has to use manual valves to operate the device.

Figs. 11 and 11A illustrate the use of the pneumatic human power amplifier module on a manual

5   material handling device 210. Manual material handling device 210 includes a pneumatic single-acting translational actuator 211 mounted horizontally on a structural support such as a ceiling or on an overhead crane 212. The piston 213 of actuator 211 is connected

10   to a ball-nut 214 of a ball-screw mechanism. The screw 215 of the ball-screw mechanism is stationary and fixed to the cylinder 216 of the actuator 211. The ball-nut 214 carries a winch 217. As supply air is pushed into the cylinder 216 of the pneumatic translational

15   actuator 211, the winch 217 rotates with the ball-nut 214 due to the force of the air (arrow A) on the face of the piston 213. The rotation of winch 217 winds or unwinds the rope 218 and causes the rope 218 to lift or lower the load 219 connected to the rope 218. Although

20   it could be mounted at any location, the pneumatic circuitry 220 is mounted on the actuator 211 for convenience and compactness. The details of the pneumatic circuitry 220 are shown in Figs. 15 and 16.

The servovalves located in the pneumatic circuitry

25   220 are controlled by the electronic controller 221 which receives control signals from the end-effector 222 over a signal cable 223. The controller 221 can be an analog circuit, a digital circuit, or a computer with electronic input/output capability.

-33-

Instead of the manual valves used in existing
material handling devices, the human operator controls
device 210 with the end-effector 222 that is attached
to the endpoint of the rope 218. The end-effector 222
5   has two subsections: the human interface subsection
224 and the load interface subsection 225. The human
interface subsection 224 includes a brace 226 that the
operator wears, a handle 227 that the operator grasps,
and a force-sensing device 292 that measures the force
10   of the operator's hand on the handle 227. The load
interface subsection 225 includes components such as
suction cups or hooks that attach to the load 219. Two
suction cups 228 are used in this application. The air
circuitry for the suction cups 228 and the logic
15   switches for controlling the vacuum for cups 228 are
not shown for the sake of clarity.

The end-effector 222 contains a sensor which
measures the magnitude of the vertical force exerted on
the handle 227 of the end-effector 222 by the human
20   operator's hand. Signals representing the forces from
the operator's hand are transmitted to the controller
221 over signal cable 223. Using these signals, the
controller 221 calculates the correct amount that a
proportional servovalve included in the pneumatic
25   circuitry 220 has to open to allow air to flow to or
from the actuator 211. The command from the controller
221 to this pneumatic circuitry is carried by signal
cable 229. The resulting motion of the piston 213 due
to this air flow rotates the winch 217 enough to either
30   raise or lower the rope 218 the correct distance that

-34-

creates enough mechanical strength to assist the
operator in the lifting task as required. All of this
happens so quickly that the operator's lifting efforts
and the device's lifting efforts are for all purposes
5   synchronized perfectly. If the operator's hand pushes
downward on the handle 227 and brace 226, the winch 217
rotates and moves the rope 218 downward, lowering the
load 219. If the operator's hand pushes upward on the
handle 227 and brace 226, the winch 217 rotates (in the
10   opposite direction) and the rope 218 moves upward,
lifting the load 219. The operator's physical
movements are thus translated into a physical assist
from the machine 210, and the machine's strength is
directly and simultaneously controlled by the human
15   operator's force on the handle 227. In summary, the
load 219 moves vertically because of the vertical
movements of both the operator's hand and the material
handling device 210.

     The three embodiments illustrated in Figs. 12-14
20   show how the pneumatic human power amplifier module can
be used in conjunction with other types of pneumatic
material handling devices. Fig. 12 shows the pneumatic
human power amplifier module connected to a material
handling device 230 which includes a pneumatic single-
25   acting translational actuator 231 hung by its piston
side 232 from a ceiling or overhead crane (not shown).
The pneumatic human power amplifier module includes the
same components as the module shown in Fig. 11, i.e.,
the end-effector 222, the pneumatic circuitry 220, and
30   the electronic controller 221. When air is pushed into

the cylinder 233 of the actuator 231, the cylinder 233
and the load 219 will move upward. Like the system of
Fig. 11, material handling device 230 adds power to the
movement of the load 219 only in the vertical

5   direction. Because the human amplifier module is a
part of the material handling device 230, the operator
no longer has to use manual valves to operate the
device 230 in order to lift loads. Instead, he/she
controls the device 230 with the end-effector 222 that

10   is attached to the endpoint of the device 230. The
actuator 231 is driven by pneumatic circuitry 220
(mainly a proportional servovalve and a directional
servovalve) that is controlled by an electronic
controller 221. The electronic controller 221 can be

15   an analog circuit, a digital circuit, or a computer
with electronic input/output capability. The
controller 221 receives signals from the end-effector
222 over a signal cable 223. Similar to the device
shown in Fig. 11, the controller 221, based on measured

20   signals from the end-effector 222 and based on the
dynamic behavior of the system, calculates how much to
open the proportional servovalve. This causes the
actuator 231 to move as necessary to either raise or
lower the end-effector 222 and the load 219 the correct

25   distance that creates enough mechanical strength to
assist the operator in the lifting task. If the
operator's hand pushes upward on the handle 227 and
brace 226, the actuator 231 lifts the load 219 upward.
If the operator's hand pushes downward on the handle

30   227 and brace 226, the actuator 231 moves the load 219

-36-

downward.   Therefore the load 219 moves vertically
because of the vertical movements of both the operator
and the material handling device 230.

     Fig. 13 illustrates a further embodiment of the
5   invention where a pneumatic human power amplifier
module is used in conjunction with a manual material
handling manipulator 240 that is mounted on a pedestal
241.   Again, the pneumatic human power amplifier module
includes pneumatic circuitry 220, electronic controller
10   221, and end-effector 222.   Unlike the previous
applications, material handling manipulator 240
manipulates loads in all directions, even though it is
usually powered only in the vertical direction to
compensate for gravity forces.   Thus, only one degree
15   of freedom of the manual material handling manipulator
240 is powered by the pneumatic single-acting
translational actuator which includes piston 242 and
cylinder 243.   In this case both the pneumatic
circuitry 220 and the controller 221 are enclosed in a
20   box 244.   Attached to the endpoint of the manipulator
240 is an end-effector 222.   The handle 227 of the end-
effector 222 is gripped by the human operator's hand
and contains a force sensor which measures the force
that the operator applies to the handle 227 in the
25   vertical direction.   Using these measurements, via
signal cable 223, the controller 221 calculates how
much to open the proportional servovalve within
pneumatic circuitry 220 to add sufficient power to
assist the operator in the lifting task.   A lifting
30   mechanism includes horizontal links 246 and 247, which

pivot about points 205a and 205b on a vertical member
248. Piston 242 and cylinder 243 are attached to pivot
points 205c and 205d, respectively. If the operator's
hand pushes upward on the handle 227 and arm brace 226,

5   air is pushed through the servovalve (inside box 244)
and hose 245 into cylinder 243. The actuator
(consisting of piston 242 and cylinder 243) expands,
and the horizontal pivoting links 246 and 247 are
pushed upward by the upward force of the piston 242.

10 If the operator's hand pushes downward on the handle
227 and brace 226, the actuator retracts and links 246
and 247 move downward. The controller 221 can be an
analog circuit, a digital circuit, or a computer with
electronic input/output capability. A vertical beam

15 249 from which the end-effector 222 is supported is
rotatable about a pivot point 207 to allow the load 219
to be moved in a horizontal plane.

        Yet another embodiment of the invention is shown
in Fig. 14. In this case, the human amplifier module

20 system is mounted on a material handling manipulator
250. Material handling manipulator 250 is similar to
material handling manipulator 240 (Fig. 13), except
that material handling manipulator 250 is hung from the
ceiling or from an overhead crane. The end-effector

25 222 mounted at the endpoint of manipulator 250 measures
the human operator's force on the end-effector 222.
Using these measurements, the controller 221 calculates
the degree to which the servovalve within pneumatic
circuitry 220 needs to open in order to cause the

30 actuator (including piston 251 and cylinder 252) to

create enough mechanical force to assist the operator
in the lifting task. If the operator's hand pushes
upward on the handle 227, the actuator contracts and
links 253 and 254 move upward. If the operator's hand
5   pushes downward on the handle 227, the actuator expands
and links 253 and 254 move downward.

Three elements of the pneumatic human power
amplifier module, namely, the pneumatic circuitry 220,
the end-effector 222, and the controller 221 will now
10   be described. Two versions of pneumatic circuitry 220,
one without and one with manual override control, are
seen in Figs. 15 and 16.

A pneumatic circuit 260 without manual override
control is shown in Fig. 15. Circuit 260 can be used
15   with any of the material handling devices shown in
Figs. 11, 12, 13, and 14. The manual material handling
system 210 depicted in Fig. 11 is used to describe
pneumatic circuit 260. The single-acting pneumatic
actuator 211 is used to lift/lower load 219 with rope
20   218. The piston 213 in single-acting actuator 211 can
be pushed in only one direction, because actuator 211
has only one port 261 for air flow. As discussed
above, the movement of the piston 213 translates into
the rotation of winch 217 due to the ball-screw
25   mechanism. The air supply, which is regulated by a
pressure regulator at a relatively constant pressure
(usually about 100 psi but in a range of from about 70
psi to about 120 psi), is sent to a three-way
proportional servovalve 262. The air supply flows
30   through the manifold 263 that is attached to the

actuator 211 for the sake of compactness. The
proportional servovalve 262 controls the flow of air
into and out of the actuator 211 based on an electronic
signal from a servovalve driving circuit (amplifier)

5   264 which is carried over the signal wire 229. The air
flow between the proportional servovalve 262 and the
actuator 211 is controlled by the computer 265 which
provides an input command to the servovalve driving
circuit (amplifier) 264. For example, when the voltage

10   command from the computer 265 to the servovalve driving
circuit (amplifier) 264 is 5 volts, the proportional
servovalve 262 allows air to flow from the air supply
port 266 to the actuator port 261; and when the voltage
command is -5 volts, the proportional servovalve 262

15   allows air to flow from the actuator port 261 to the
exhaust port 267 of the servovalve. Note that the
above arrangement lets air flow in both directions,
into and out of the actuator 211 through actuator port
261. The air flow at any voltage command between -5

20   volts and 5 volts is a linear function of the voltage
command to the valve driving circuit 264, with the air
flow from air supply port 266 to the actuator port 261
increasing linearly as the voltage increases from 0 to
5 volts, and with the air flow from actuator port 261

25   to the exhaust port 267 increasing linearly as the
voltage decreases from 0 to -5 volts. Of course, at a
particular voltage command from the computer 265 (zero
volt in this example) there is no air flow in actuator
port 261. As the proportional servovalve 262 opens the

30   flowpath from air supply port 266 to the actuator port

-40-

261, the air flow into the actuator 211 increases,
which moves the piston 213 to the right. As the
proportional servovalve 262 opens the flowpath from the
actuator port 261 to the exhaust port 267, the air in
5   the cylinder 216 is allowed to vent. This causes the
weight of the load 219 to turn the winch 217 and moves
the piston 213 to the left. An optional passage 268
including a manual valve 269 can be installed in
parallel with the proportional sevovalve 262 to provide
10   a biased flow into the actuator 211 if the proportional
servovalve is not able to provide such a biased flow.
A small opening of valve 269 allows for an upward bias
force on cable 218. The technique for generating the
control signal to the servovalve driving circuit
15   (amplifier) 264 is described below.

In one embodiment, proportional servovalve 262 is
the model NVEF, and servovalve driving circuit
(amplifier) 264 is the model VEA, both of which are
available from SMC Inc. There are two kinds of
20   servovalves available in the market: flow control
proportional servovalves and pressure control
proportional servovalves. Although in the above
description proportional servovalve 262 is a flow
control servovalve, a pressure control servovalve could
25   be used in place of the flow control servovalve.

The pneumatic circuit shown in Fig. 15 does not
include a back-up system to allow manual maneuvering of
the load 219 without the end-effector 222. In other
words, there is no pushbutton, keyboard, switch, or
30   manual valve for operating the actuator 211 in case of

-41-

an electric power failure or the malfunctioning of the
computer 265, end-effector 222 or servovalve driving
circuit 264.   To remedy this problem, manual override
air circuitry can be added to the automated circuit of

5   Fig. 15.   Fig. 16 shows an enhanced pneumatic circuit
270 that incorporates the manual override mode.
Pneumatic circuit includes a three-way directional
servovalve 271 and two normally-closed, usually thumb-
operated "Up" 272 and "Down" 273 valves.   Directional

10   servovalve 271 may be a model NVS valve available from
SMC Inc.   In this system, the flow from the air supply
port 266 is directed to one of two circuits by
directional servovalve 271, which is controlled by a
momentary deadman switch 274 on the end-effector 222.

15   Note that Fig. 16 shows the three-way directional
servovalve 271 in its normal position, that is, when it
is not activated electrically by the deadman switch
274.   When the three-way directional servovalve 271 is
not activated, the air is directed through the manual

20   control portion of the circuit, allowing the operator
to use the manual "Up" 272 and "Down" 273 valves.   This
occurs in two situations: either when the electric
power fails or when the operator is not holding onto
the end-effector 222.   In either case the system turns

25   to manual mode and the operator will be able to operate
the device manually.   In this manual mode when the
operator activates the "Up" valve 272, the air flows
from the air supply port 266, through the hose 275,
through the "Up" valve 272, through the hose 276,

30   through the three-way servovalve 271, and through

-42-

passage 261 to the actuator 211. This moves the piston
213 to the right and lifts the load 219. When the
operator activates the "Down" valve 273, the weight of
the load 219 causes the pulley 217 to turn and move the
5 piston 213 to the left and lower the load 219. The air
in the actuator 211 is then exhausted through the
three-way directional servovalve 271, through the hose
276, and through the "Down" valve 273, to the
atmosphere (arrow E).

10   If the deadman switch 274 is depressed, (i.e., the
operator is holding onto the handle 227 of the end-
effector 222), the three-way directional servovalve 271
is activated and hose 277 will be connected to the
actuator 211, bypassing the manual circuitry. The
15 proportional servovalve 262 then controls the flow of
air into and out of the actuator 211 based on the
signal from the controller 221 which is carried by
signal wire 229. In other words, once the deadman
switch 274 is activated, the system operates in the
20 same manner as the system shown in Fig. 15, and the
operator's activation of the "Up" 272 or "Down" 273
valves will have no effect on the system behavior.

     Fig. 16 shows that the three-way directional
servovalve 271 is activated directly by the signal
25 coming from the deadman switch 274 via the signal wire
278. However there are other ways to activate the
three-way directional servovalve 271 which will produce
the same performance. For example, the three-way
directional servovalve 271 can be activated indirectly
30 by the deadman switch 274 via a relay. In such an

-43-

embodiment the deadman switch 274 triggers a relay
located in controller 221, and the relay activates the
three-way directional servovalve 271. This is
necessary when the voltage required to activate the
5   three-way directional valve 271 is different from the
voltage required to activate the deadman switch 274.

Fig. 17 shows a detailed view of end-effector 222.
End-effector 222 includes a human interface subsection
224 and a load interface subsection 225. Human
10   interface subsection 224 includes the handle 227 which
is grasped by the operator and thus measures the human
force imposed on end-effector 222 (not the load force).
Load interface subsection 225 includes a hook or a
suction cup 228 or any other type of device that can be
15   used to hold or support an object. An eyelet 281 is
mounted in bracket 282 for connecting bracket 282 to a
rope 218 if this end-effector 222 is used with the
material handling device 210 shown in Fig. 11. Bracket
282 also has bolt holes for connecting the end-effector
20   222 to the material handling devices shown in Figs. 12,
13 and 14. Brace 226 is connected to the human
interface subsection 224 and has two components which
rotate relative to each other via the hinge 283 so as
allow the operator to bend his/her wrist in the
25   horizontal plane comfortably. Brace 226 does not allow
the operator to bend his/her wrist in the vertical
plane. A lever 303 is connected to the handle 227 and
activates the deadman switch 274 (see Fig. 18) when the
operator grips the handle 227. All signal cables from

the force measuring device 292 and the deadman switch
274 are attached to connector 284.

Fig. 18 is a cross-sectional partially broken away
view of the end-effector 222. A ball-screw mechanism
5   291 translates the vertical displacement of handle 227
into a rotary displacement which is measured by an
angle measuring device 292. The handle 227 is
connected to the ball-nut portion 293 of the ball-screw
mechanism 291. The screw 294 of the ball-screw
10 mechanism 291 is secured by the inner race of a bearing
system 295. The bearing system 295, here a double row
bearing, includes any combination of bearing(s) that
allows rotation of the screw 294 while supporting
vertical and horizontal forces. A pair of angular
15 contact bearings could also be used. Because of the
connection between the screw 294 and the inner race of
the bearing system 295, the inner race and the screw
294 turn together. The outer race of the bearing
system 295 is held in a bracket 282 by a retaining ring
20 296 which is fixed to the bottom of the bracket 282. A
shaft 297 extends downwards from the lower end of the
screw 294 along the axis of the handle 227. An upper
coil spring 298 is positioned around the shaft 297
between the screw 294 and a shoulder 299 formed inside
25 the handle 227. A lower coil spring 300 is positioned
around the shaft 297 between the stop 301 fixed to the
shaft 297 and the shoulder 299 formed inside the handle
227. Stop 301 can be a clamp ring. Thus the coil
spring 298 urges the handle 227 downward, and the coil
30 spring 300 urges the handle 227 upward. Together the

springs 298 and 300 let the handle 227 move axially
with respect to the screw 294 and the shaft 297. The
springs 298 and 300 return the handle 227 to an
equilibrium position when the handle 227 is not pushed.

5   The bracket 302 mounted on the handle 227 prohibits the
rotation of the handle 227 relative to the screw 294.
The handle 227, which is connected to the ball-nut 293
of the ball-screw mechanism 291, is held by the
operator.

10   If the handle 227 is moved up and down, then the
screw 294 turns. The amount of rotation of the screw
294 depends on the lead of the screw 294. For example,
if the lead is 1/2 inch, then for every 1/2 inch motion
of the handle 227, the screw 294 turns one revolution.

15 The angle measuring device 292 connected to the top of
the bracket 282 measures the rotation of the screw 294.
The angle measuring device 292 can be an optical rotary
encoder, a magnetic rotary encoder, a rotary
potentiometer, a RVDT (Rotary Variable Differential

20 Transformer), an analog resolver, a digital resolver, a
capacitive rotation sensor, or a Hall effect sensor.
The angle measuring device 292 produces a signal
proportional to the rotation of the screw 294.

        To maintain tension in the rope 218, an upward

25 velocity is imposed on the rope 218 when there is no
load on the system (assuming that the end-effector 222
itself is negligibly light). In this case, only one
spring, either a compression spring beneath shoulder
299 or a tension spring above shoulder 299 is

30 sufficient to force the handle 227 upward. When using

-46-

the end-effector 222, the operator grasps the handle

227. When the operator initiates an upward motion, the

handle 227 (connected to the ball-nut 293) moves

upward, causing the screw 294 to turn (e.g.,

5   clockwise). This motion is recorded by the angle

measuring device 292. The signal generated by the

angle measuring device 292 is then transmitted to the

controller 221 (Fig. 1). The actuator 211 turns

appropriately, causing an upward motion of the rope 218

10   and the end-effector 222. This motion lifts the load

219 and the end-effector 222 together. Similarly, when

the operator initiates a downward motion, the actuator

211 turns appropriately in the opposite direction,

causing a downward motion of the rope 218 and the end-

15   effector 222. Thus, in the end-effector 222, the

vertical displacement of handle 227 relative to bracket

282 (a displacement that is proportional to the human

force) is measured. This measurement is fed to the

controller 221. Regardless of the type of displacement

20   sensor used in this device and its installation

procedure, this end-effector 222 is designed to measure

only the human force in the vertical direction. The

end-effector 222 does not measure the load force. The

deadman/safety switch 274 is installed to transfer the

25   actuator 211 to another control mode (i.e., position

control mode) or to turn the system off when the

operator leaves the system. A lever 303 is connected

to the handle 227 to activate the deadman/safety switch

274 when the operator grasps the handle 227.

-47-

The sole purpose of the springs 298 and 300
installed in the end-effector 222 is to bring the
handle 227 back to an equilibrium position when no
force is imposed on the handle 227 by the operator.
5   Figs. 17 and 18 show the end-effector 222 using
compression springs 298 and 300. Other kinds of springs
can be used, such as cantilever beam springs, tension
springs or belleville springs. Basically, any
resilient element capable of bringing the handle 227
10   back to its equilibrium position will be sufficient.
The structural damping in the springs or the friction
in the moving elements of the end-effector 222 (e.g.,
bearings) should provide sufficient damping in the
system to provide stability.

15   Next the controller 221 associated with this human
power amplifier module will be described. The force or
displacement sensor 292 (Fig. 18) in the end-effector
222 delivers a signal to the controller 221 (Fig. 11)
that is used to control the actuator 211 and to send an
20   appropriate signal to the pneumatic circuitry 220. If
e is the input command to the pneumatic circuitry 220,
then, in the absence of any other external force on the
actuator 211, the linear velocity v of the outermost
point of the end-effector 222 velocity v can be
25   represented by:

$$v = G_o \cdot e \qquad\qquad (8)$$

where G_o is the transfer function relating the input
30   command e to end-effector velocity v. (A downward

-48-

rope velocity is considered positive in this analysis.)
In addition to the input command e from the controller
the forces imposed on the end-effector also affect the
end-effector velocity. There are two forces imposed on
5   the end-effector which affect the end-effector
velocity: a force f which is imposed by the operator's
hand, and a force, p, which is imposed by the load on
the end-effectors (see Fig. 19). The input command e
and the forces on the end-effectors contribute to the
10   end-effector speed such that:

$$v = G_O \cdot e + S_O(f + p) - v_{up} \qquad (9)$$

where S_O is the actuator sensitivity function which
15   relates the external forces to the endpoint velocity v.
S_O is defined as the downward velocity of the end-
effector if one unit of impulse tensile force is
imposed on the rope. If a velocity controller is
designed for the actuator so that S_O is small, the
20   actuator has only a small response to the imposed
tensile force on the rope. A high-gain controller in
the closed-loop velocity system results in a small S_O
and consequently a small actuator velocity in response
to forces imposed on the end-effector. To develop
25   tension in the rope at all times if the module is to be
used with the device of Fig. 11, an upward biased rope
velocity, v_{up}, is introduced to the system. M is the
mass of the object being lifted. E and H are the
impedances of the end-effector spring and human arm,
30   respectively.

-49-

A reasonable performance specification for the
actuator is the level of amplification of the operator
force f that is applied to the end-effector. If the
force amplification is large, a small force applied by
5   the operator results in a large force being applied to
the load via the device. If the amplification is
small, a small force applied by the operator results in
a small force being applied to the load via the device.
Consequently, if the amplification is large, the
10   operator "feels" only a small percentage of the force
required to lift the load. Importantly, at any chosen
amplification, the operator still retains a sensation
of the dynamic characteristics of the free mass, yet
the load essentially "feels" lighter. Thus the system
15   performance can be defined as a number that represents
the force amplification. For example, when the force
amplification of the system is programmed to be 5, for
every 5 pound-force on the end-effector the operator
imposes (and feels) one pound on the end-effector. The
20   following explains how to guarantee this performance
for the device. The operator force f is measured and
passed through the controller 221 which delivers a
signal e to the actuator 211. If the transfer function
of the controller is represented by K, then the output
25   of the controller, e, is equal to K·f.

Substituting for e in equation (9) results in the
following equation for the rope velocity v:

$$v = G_O \cdot K \cdot f + S_O(f + p) - v_{up} \qquad (10)$$

30

-50-

Any variation in the load's force on the end-effector, Δp, will result in a variation in the force on the operator's hand according to the following equation if no change in maneuvering speed is expected:

5

$$\left(\frac{G_o K}{S_O} + 1\right)\Delta f = -\Delta p \qquad (11)$$

where Δf is the change in the human force on the end-effector. The term (GoK/So + 1) in equation (11) is
10 the force amplification factor. This term relates the variation in the load force, Δp, to the variation of the human force, Δf. The larger K is chosen to be, the greater the force amplification in the system. K must be designed to yield an appropriate force
15 amplification.

Fig. 19 shows diagramatically how the human force and load force are generated. As Fig. 19 indicates, K may not be arbitrarily large. Rather, the choice of K must guarantee the closed-loop stability of the system
20 shown in Fig. 19. The operator force f is a function of the human arm impedance H and sensor dynamics E, whereas the load force p is a function of the load mass M. There are many model-based algorithms available in the control literature capable of providing a transfer
25 function K for the controller which stabilizes the system such that the load and end-effector follow the operator's hand.

Although particular embodiments of the invention are illustrated in the accompanying drawings and

-51-

described in the foregoing detailed description, it is understood that the invention is not limited to the embodiments disclosed, but is intended to embrace any alternatives, equivalents, modifications and/or

5 arrangements of elements falling within the scope of the invention as defined by the following claims. The following claims are intended to cover all such modifications and alternatives.

CLAIMS

I claim:

1.   A pneumatic human power amplifier module for
connection to a pneumatic actuator for driving a
5   lifting device to lift or lower a load, said module
comprising:

an end-effector for engaging the load, said
end-effector including a sensor for detecting a
human force on the end-effector;

10   a controller arranged to receive an output
signal from said sensor; and

a pneumatic circuit attachable to said
pneumatic actuator, said pneumatic circuit being
arranged to receive an output signal from said
15   controller and to control an air flow into and out
of said pneumatic actuator such that said
pneumatic actuator causes said lifting device to
impose a device force on the load such that the
total of said human force and said device force
20   taken together causes the end-effector and the
load to follow an operator's hand as said operator
manipulates said end-effector and said load.

2.   The pneumatic human power amplifier module of
25   Claim 1 wherein said device force is larger than said
human force.

3.   The pneumatic human power amplifier module of
Claim 1 wherein said human force is equal to a

predetermined percentage of said total of said human
force and said device force.

    4.   The pneumatic human power amplifier module of
5   Claim 1 wherein said pneumatic circuit comprises a flow
control proportional servovalve for controlling an air
flow into and out of said pneumatic actuator.

    5.   The pneumatic human power amplifier module of
10 Claim 1 wherein said pneumatic circuit comprises a
pressure control proportional servovalve for
controlling the pressure of an air flow into and out of
said pneumatic actuator.

15   6.   The pneumatic human power amplifier module of
Claim 4 or 5 wherein said pneumatic circuit comprises
an UP valve and a DOWN valve for overriding said
proportional servovalve, said UP valve being operable
manually to cause an air flow into said pneumatic
20 actuator, said DOWN valve being operable manually to
cause an air flow out of said pneumatic actuator.

    7.   The pneumatic human power amplifier module of
Claim 6 wherein said UP valve is connected in parallel
25 with said proportional servovalve for manually
controlling an air flow from a supply pressure to said
pneumatic actuator.

    8.   The pneumatic human power amplifier module of
30 Claim 6 wherein said DOWN valve is connected in

parallel with said proportional servovalve for manually

controlling an air flow out of said pneumatic actuator

to the ambient atmosphere.

5   9.   The pneumatic human power amplifier module of

Claim 6 wherein said UP and DOWN valves are for

allowing manual operation of said lifting device in the

event of a failure of said controller and/or said

sensor.

10

          10.   The pneumatic human power amplifier module of

Claim 6 wherein said UP and DOWN valves are for

allowing manual operation of said lifting device in the

event of an electric power failure.

15

          11.   The pneumatic human power amplifier module of

Claim 6 wherein said pneumatic circuit comprises a

directional servovalve and said end-effector comprises

a deadman switch, said directional servovalve providing

20   an air passage between said proportional servovalve and

said pneumatic actuator when said deadman switch is in

a first position.

          12.   The pneumatic human power amplifier module of

25   Claim 11 wherein said directional servovalve is

arranged to receive an output signal from said deadman

switch.

          13.   The pneumatic human power amplifier module of

30   Claim 11 wherein said directional servovalve provides

an air passage between said pneumatic actuator and said
UP and DOWN valves when said deadman switch is in a
second position.

5   14.   The pneumatic human power amplifier module of
Claim 13 wherein said UP and DOWN valves allow said
pneumatic actuator to be operated manually when deadman
switch is in said second position.

10   15.   The pneumatic human power amplifier module of
Claim 1 wherein said end-effector comprises a human
interface subsection for interfacing with an operator
and a load interface subsection for engaging a load.

15   16.   The pneumatic human power amplifier module of
Claim 15 wherein said human interface subsection
comprises a handle to be grasped by an operator.

         17.   The pneumatic human power amplifier module of
20 Claim 16 wherein said pneumatic circuit comprises a
directional servovalve and said end-effector comprises
a deadman switch, an output signal from said deadman
switch actuating said directional servovalve so as to
provide an air passage between said proportional
25 servovalve and said pneumatic actuator when said
deadman switch is in a first position.

         18.   The pneumatic human power amplifier module of
Claim 17 wherein said deadman switch is moved from a

-56-

second position to said first position when an operator
grasps said handle.

19. The pneumatic human power amplifier module of
Claim 15 wherein said human interface subsection
further comprises a brace for engaging the operator's
forearm.

20. The pneumatic human power amplifier module of
Claim 19 wherein said brace encircles the operator's
forearm and is connected to two ends of said handle
with a vertical hinge such that the operator can flex
his or her wrist only in a horizontal plane when
lifting a load with the end-effector.

21. The pneumatic human power amplifier module of
Claim 15 wherein said end-effector comprises a position
sensor for detecting a relative position of said handle
with respect to said load interface subsection, an
output signal from said position sensor representing
said relative position of said handle with respect to
said load interface subsection.

22. The pneumatic human power amplifier module of
Claim 21 wherein said human interface subsection
comprises a ball-screw arrangement for converting a
linear motion of said handle relative to said load
interface subsection into a rotary motion, said ball-
screw arrangement comprising a nut portion and a screw
portion.

23. The pneumatic human power amplifier module of
Claim 21 wherein said human interface subsection
comprises a lead-screw arrangement for converting a
5 linear motion of said handle relative to said load
interface subsection into a rotary motion, said lead-
screw arrangement comprising a nut portion and a screw
portion.

10   24. The pneumatic human power amplifier module of
Claim 22 or 23 wherein said screw portion is rotatably
held by the load interface subsection and said nut
portion is constrained to move linearly along a major
axis of said screw portion.
15

25. The pneumatic human power amplifier module of
Claim 22 or 23 wherein said nut portion is attached to
said handle.

20   26. The pneumatic human power amplifier module of
Claim 22 or 23 wherein said position sensor comprises
an angle-measuring device for measuring a rotation of
said screw portion relative to said nut portion.

25   27. The pneumatic human power amplifier module of
Claim 26 wherein said angle-measuring device is
selected from the group consisting of a rotary
potentiometer, a rotary optical encoder, and a rotary
magnetic encoder.

30

28. The pneumatic human power amplifier module of
Claim 22 or 23 wherein said end-effector comprises at
least one spring for maintaining said handle in an
equilibrium position when no force is imposed on said
5   handle by an operator.

29. The pneumatic human power amplifier module of
Claim 15 wherein said load interface subsection is
designed for attachment to an endpoint of said lifting
10   device.

30. The pneumatic human power amplifier module of
Claim 15 wherein said load interface subsection
comprises a mechanism for engaging a load.

15

31. The pneumatic human power amplifier module of
Claim 30 wherein said mechanism for engaging a load
comprises at least one suction cup.

20   32. The pneumatic human power amplifier module of
Claim 30 wherein said mechanism for engaging a load
comprises at least one hook.

33. A human power amplifier apparatus comprising:
25   a lifting device;
           a pneumatic actuator; and
           a pneumatic human power amplifier module
     coupled to said pneumatic actuator for driving
     said lifting device to lift or lower a load, said
30   module comprising:

an end-effector for engaging the load,

said end-effector including a sensor for

detecting a human force on the end-effector;

a controller arranged to receive an

5   output signal from said sensor; and

a pneumatic circuit coupled to said

pneumatic actuator, said pneumatic circuit

being arranged to receive an output signal

from said controller and to control an air

10   flow into and out of said pneumatic actuator

such that said pneumatic actuator causes said

lifting device to impose a device force on

the load such that said human force and said

device force together lift the load.

15

34.   The human power amplifier apparatus of Claim

33 wherein said human force is equal to a predetermined

percentage of a total of said human force and said

device force.

20

35.   A method by which a human operator

manipulates a load comprising the steps of:

gripping an end-effector with said operator's

hand;

25   using the end-effector to engage the load;

applying an operator force against said end-

effector;

measuring said operator force;

using said measured operator force to control a

30   flow of air into a pneumatic actuator; and

controlling said flow of air into said pneumatic
actuator such that said pneumatic actuator causes a
lifting device to transmit a device force to said end-
effector such that said end-effector and said load
5   follow said operator's hand.

        36.   The method of Claim 35 wherein the step of
controlling comprises controlling said flow of air such
that said operator force is equal to a predetermined
10   percentage of a total of said operator force and said
device force.

        37.   The method of Claim 35 wherein the step of
controlling comprises controlling said flow of air such
15   that said operator force is less than said device
force.

        38.   The method of Claim 35 wherein the step of
controlling said flow of air comprises providing a
20   first signal representative of said measured operator
force to a computer and using said computer to generate
a second signal to a proportional servovalve.

        39.   A human power amplifier apparatus comprising:
25   a lifting device;
               a pneumatic actuator; and
               a pneumatic human power actuator module
        coupled to said pneumatic actuator for driving
        said lifting device to lift or lower a load, said
30   module comprising:

an end-effector for engaging the load,
said end-effector including a sensor for
detecting a human hand motion in the end-
effector;

5   a controller arranged to receive an
output signal from said sensor; and

a pneumatic circuit coupled to said
pneumatic actuator, said pneumatic circuit
being arranged to receive an output signal
10   from said controller and to control an air
flow into said pneumatic actuator such that
said pneumatic actuator causes said lifting
device to impose a device force on the load
such that said human force and said device
15   force together lift the load.

40. An end-effector for use in a human power
amplifier system, said end-effector comprising:

a load interface subsystem for making
contact between said end-effector and a load;

20   a human interface subsystem comprising a
handle and a force sensor, said force sensor
being for measuring a force imposed on said
handle by a human operator and being capable
of generating an electrical signal
25   representative of a magnitude of said force.

41. The end-effector of Claim 40 wherein said
force sensor is interposed between said handle and said

-62-

load interface subsystem.

42. The end-effector of Claim 40 wherein said force sensor comprises a piezoelectric element.

5

43. The end-effector of Claim 40 wherein said force sensor comprises a strain gauge.

44. The end-effector of Claim 43 wherein said

10   strain gauge is a metallic strain gauge.

45. The end-effector of Claim 43 wherein said strain gauge is a semiconductor strain gauge.

15   46. The end-effector of Claim 40 wherein said force sensor comprises a resilient member and a device for measuring a displacement of said resilient member.

47. The end-effector of Claim 46 wherein said

20   resilient member comprises a spring.

48. The end-effector of Claim 40 wherein said end-effector further comprises a ball-screw arrangement for transforming a linear motion of said handle into a

25   rotary motion, said ball-screw arrangement comprising a nut portion and a screw portion.

49.   The end-effector of Claim 40 wherein said

end-effector further comprises a lead screw arrangement

for transforming a linear motion of said handle into a

rotary motion, said lead screw arrangement comprising a

5   nut portion and a screw portion.

50.   The end-effector of Claim 48 or 49 wherein

said handle is a part of said nut portion and is

constrained to move linearly along a longitudinal axis

10   of said screw portion.

51.   The end-effector of Claim 48 or 49 further

comprising an angle measuring device for measuring a

rotation of said screw portion relative to said nut

15   portion.

52.   The end-effector of Claim 51 wherein said

angle measuring device comprises a rotary optical

encoder.

20

53.   The end-effector of Claim 51 wherein said

angle measuring device comprises a rotary

potentiometer.

25   54.   The end-effector of Claim 51 wherein said

angle measuring device comprises a rotary magnetic

encoder.

55.   The end-effector of Claim 51 wherein said
angle measuring device comprises a rotary variable
differential transformer.

5

56.   The end-effector of Claim 51 wherein said
angle measuring device comprises an analog resolver.

57.   The end-effector of Claim 51 wherein said
10   angle measuring device comprises a digital resolver.

58.   The end-effector of Claim 51 wherein said
angle measuring device comprises a capacitive rotation
sensor.

15

59.   The end-effector of Claim 51 wherein said
angle measuring device comprises a Hall effect sensor.

60.   The end-effector of Claim 40 wherein said
20   human interface subsystem comprises a linear ball
spline shaft mechanism wherein said handle is a part of
a ball-nut portion of said linear ball spline shaft
mechanism and a shaft portion of said linear ball
spline shaft mechanism is fixed to said load interface
25   subsystem.

61. The end-effector of Claim 40 wherein said
human interface subsystem comprises a linear bushing
mechanism wherein said handle is a part of a bushing
portion of said linear bushing mechanism and a shaft
5   portion of said linear bushing mechanism is fixed to
said load interface subsystem.

62. The end-effector of Claim 60 further
comprising a linear potentiometer for measuring a
10   linear displacement of said ball-nut portion relative
to said shaft portion.

63. The end-effector of Claim 60 further
comprising a linear optical encoder for measuring a
15   linear displacement of said ball-nut portion relative
to said shaft portion.

64. The end-effector of Claim 60 further
comprising a linear magnetic encoder for measuring a
20   linear displacement of said ball-nut portion relative
to said shaft portion.

65. The end-effector of Claim 60 further
comprising a linear variable differential transformer
25   for measuring a linear displacement of said ball-nut
portion relative to said shaft portion.

66. The end-effector of Claim 60 further comprising a capacitive displacement sensor for measuring a linear displacement of said ball-nut portion relative to said shaft portion.

5

67. The end-effector of Claim 60 further comprising an eddy current proximity sensor for measuring a linear displacement of said ball-nut portion relative to said shaft portion.

10

68. The end-effector of Claim 60 further comprising a variable inductance proximity sensor for measuring a linear displacement of said ball-nut portion relative to said shaft portion.

15

69. The end-effector of Claim 40 wherein said load interface subsystem comprises at least one suction cup.

20   70. The end-effector of Claim 40 wherein said load interface subsystem comprises an angle piece for interacting with an edge of a box-shaped load.

71. The end-effector of Claim 40 wherein said
25   load interface subsystem comprises a C-shaped member for placement under a human armpit.

-67-

72.   The end-effector of Claim 40 further comprising a means for attaching a line to said end-effector.

5   73.   The end-effector of Claim 40 further comprising a brace attached to said handle.

74.   A human power amplifier system comprising:

an end-effector comprising a human
10   interface subsystem for interfacing with an operator and a load interface subsystem for interfacing with a load, said human interface subsystem comprising a force sensor for measuring a human force imposed on said end-
15   effector;

an actuator for providing power to lift said end-effector; and

a controller, said controller being coupled to said force sensor so as to receive
20   an output signal generated by said force sensor and being coupled to said actuator so as to provide an input signal to said actuator, a magnitude of said output signal from said force sensor varying gradually as a
25   function of said magnitude of said human force.

75. The human power amplifier system of Claim 74 wherein said actuator comprises an electric motor.

76. The human power amplifier system of Claim 74
5 wherein said actuator is air-powered.

77. The human power amplifier system of Claim 74 wherein said actuator is hydraulic.

10   78. The human power amplifier system of Claim 74 further comprising a line coupled to said end-effector for enabling said actuator to lift said end-effector.

79. The human power amplifier system of Claim 74
15 wherein a speed of said actuator is determined by said magnitude of said human force imposed on said end-effector, as measured by said force sensor.

80. The human power amplifier system of Claim 74
20 further comprising a second end-effector coupled to said end-effector via a line, said line running over at least one pulley, said second end-effector comprising a human interface subsystem for interfacing with said operator and a load interface subsystem for interfacing
25 with a load.

81.   The human power amplifier system of Claim 80
wherein said second end-effector further comprises a
force sensor for measuring a human force imposed on
said second end-effector, said controller being coupled
5   to said second force sensor so as to receive a second
output signal from said second force sensor.

82.   A method of lifting a load comprising the
steps of:

10   providing an actuator for providing an
actuator force for lifting said load;
                      providing an end-effector for providing
an interface between a human operator and
said load;

15   causing said end-effector to engage said
load;
                      detecting a magnitude of a human force
imposed by said operator on said end-effector
as said operator lifts said end-effector,
20   said magnitude of said human force varying
gradually as said operator lifts said end-
effector;
                      using said magnitude of said human force
to regulate said actuator; and
25   causing said actuator to lift said load.

83. The method of Claim 82 wherein said magnitude of said human force is used to determine a velocity of said actuator.

5   84. The method of Claim 82 comprising the further step of causing said actuator to lift said load when said magnitude of said human force is equal to zero.

85. The end-effector of Claim 61 further
10 comprising a linear potentiometer for measuring a linear displacement of said bushing portion relative to said shaft portion.

86. The end-effector of Claim 61 further
15 comprising a linear optical encoder for measuring a linear displacement of said bushing portion relative to said shaft portion.

87. The end-effector of Claim 61 further
20 comprising a linear magnetic encoder for measuring a linear displacement of said bushing portion relative to said shaft portion.

88. The end-effector of Claim 61 further
25 comprising a linear variable differential transformer for measuring a linear displacement of said bushing portion relative to said shaft portion.

-71-

89.   The end-effector of Claim 61 further
comprising a capacitive displacement sensor for
measuring a linear displacement of said ball-nut

5   bushing portion relative to said shaft portion.

90.   The end-effector of Claim 61 further
comprising an eddy current proximity sensor for
measuring a linear displacement of said bushing portion

10   relative to said shaft portion.

91.   The end-effector of Claim 61 further
comprising a variable inductance proximity sensor for
measuring a linear displacement of said bushing portion

15   relative to said shaft portion.

92.   The human power amplifier system of Claim 74
wherein said output signal is an electrical signal.

20   93.   The method of Claim 82 wherein the step of
detecting a magnitude of a human force imposed by said
operator on said end-effector comprises generating an
electrical signal representative of said magnitude of
said human force.

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94.   The method of Claim 82 wherein the step of
regulating said actuator comprises programming a

-72-

controller such that a ratio of a change in the human

force to a change in the actuator force remains

substantially constant.

5   95. The method of Claim 94 comprising the step of

programming said controller such that said ratio is

equal to GK/S + 1, where G is a transfer function of

said actuator, K is transfer function of said

controller and S is a sensitivity function of said

10   actuator.

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Controller

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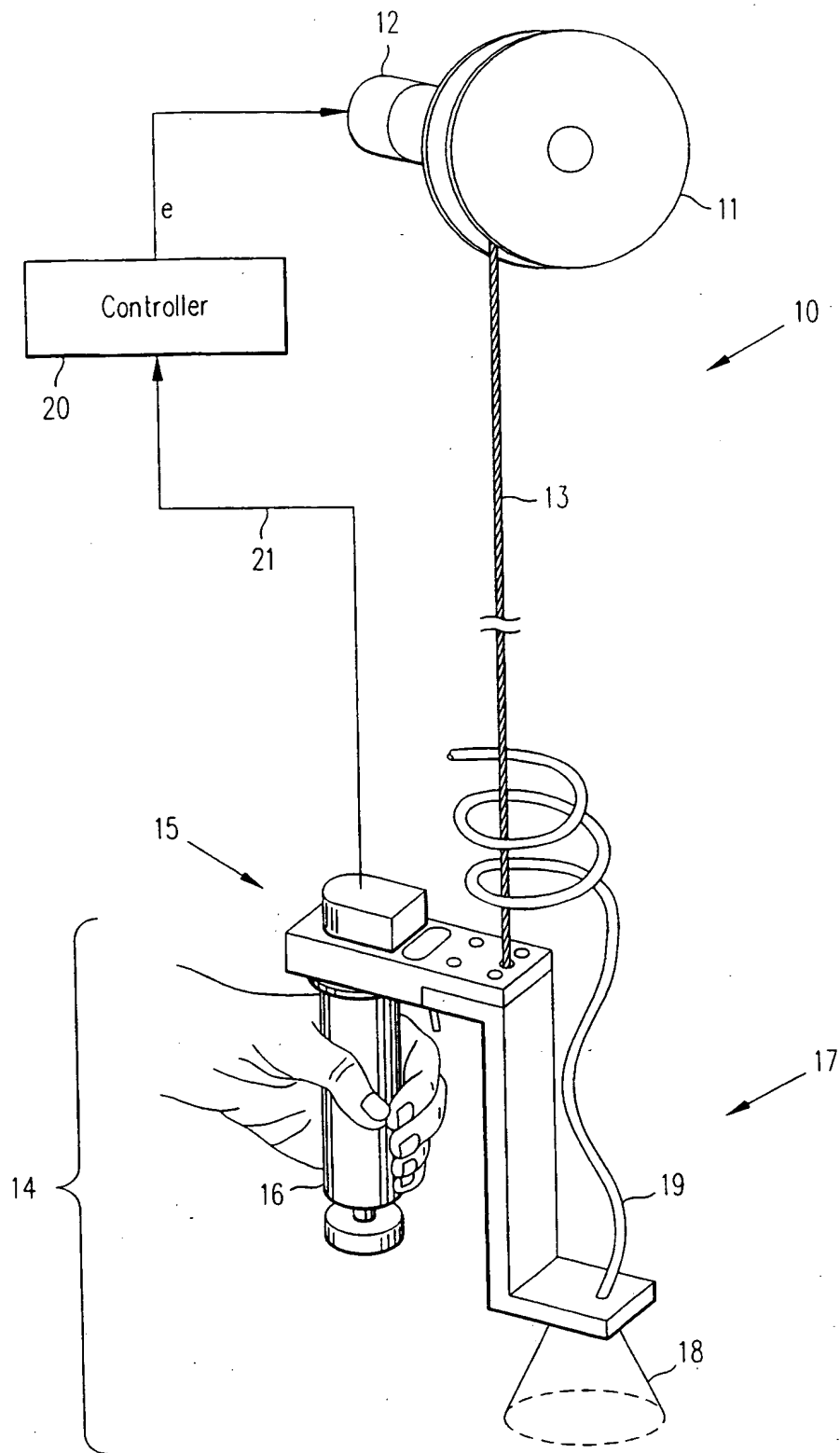
FIG. 1

FIG. 2

SUBSTITUTE SHEET (RULE 26)
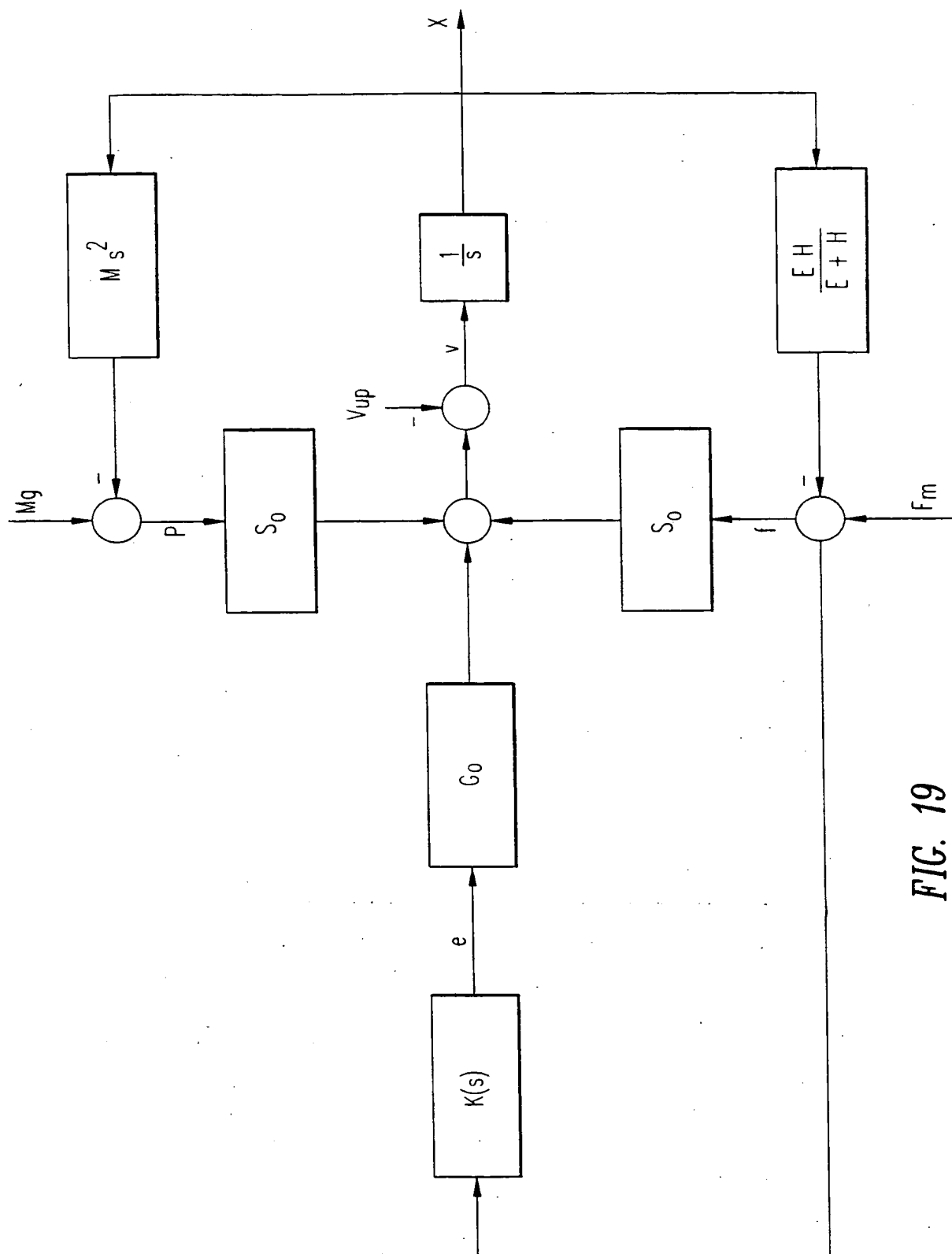
FIG. 3

FIG. 4

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FIG. 5

FIG. 6

FIG. 7

FIG. 8

FIG. 9

FIG. 10

11/19

FIG. 11A

FIG. 11

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12/19

FIG. 12

FIG. 13

Controller
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Pneumatic
Circuitry
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FIG. 14

FIG. 15

BNSDOCID: <WO   9843911A1 I >

FIG. 16

FIG. 17

FIG. 18

FIG. 19

INTERNATIONAL SEARCH REPORT

A.   CLASSIFICATION OF SUBJECT MATTER

IPC(6)   :B66D 1/00

US CL   :254/270, 331, 360; 212/285; 414/5

According to International Patent Classification (IPC) or to both national classification and IPC

B.   FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. :   254/266, 270, 274, 331, 360; 212/330, 331, 338, 285; 414/2, 4, 5

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C.   DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2,940,608 A (UNDERWOOD ET AL) 14 June 1960 (14/06/60), see column 1, lines 32-36.	1-95
A	US 3,384,350 A (POWELL) 21 May 1968 (21/05/68), see column 1, lines 64-68.	1-95
A	US 3,791,627 A (STONE ET AL.) 12 February 1974 (12/02/74)	1-95
A	US 3,921,959 A (ULBING) 25 November 1975 (25/11/75)	1-95
A	US 3,940,110 A (MOTODA) 24 February 1976 (24/02/76)	1-95
A	US 4,500,074 A (FOX ET AL) 19 February 1985 (19/02/85)	1-95

| X	Further documents are listed in the continuation of Box C.		See patent family annex.

	Special categories of cited documents	"T"	later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A"	document defining the general state of the art which is not considered to be of particular relevance		
"E"	earlier document published on or after the international filing date	"X"	document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"L"	document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"Y"	document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"O"	document referring to an oral disclosure, use, exhibition or other means		
"P"	document published prior to the international filing date but later than the priority date claimed	"&"	document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
01 JUNE 1998	1 6 JUL 1998
Name and mailing address of the ISA/US Commissioner of Patents and Trademarks Box PCT Washington, D.C. 20231 Facsimile No. (703) 305-3230	Authorized officer KATHERINE A. MATECKI Telephone No. (703) 306-4177

Form PCT/ISA/210 (second sheet)(July 1992)*

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 4,557,659 A (SCAGLIA) 10 December 1985 (10/12/85)	1-95
A	US 5,489,032 A (MAYHALL, JR., ET AL) 6 February 1996 (06/02/96)	1-95
A	US 5,520,368 A (BRAESCH ET AL) 28 May 1996 (28/05/96)	1-95
A	US 5,556,077 A (BRAESCH ET AL) 17 September 1996 (17/09/96)	1-95